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[54] **METHOD AND APPARATUS FOR APPLYING A FILM TO A SUBSTRATE SURFACE BY DIODE SPUTTERING**

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[52] **U.S. Cl.** **204/192**, 204/298

[51] **Int. Cl.** **C23c 15/00**

[58] **Field of Search** 204/192, 298

[56] **References Cited**

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[57] **ABSTRACT**

Diode sputtering apparatus deposits a film on a substrate surface while protecting the substrate against overheating and other adverse effects due to electron bombardment. A magnetic field, transverse to an electric field between the cathode and substrate surface, is rotated about the cathode-substrate axis to deflect electrons submitted from the cathode into paths clear of the substrate surface. Further advantages in uniformity and increased rate of depositions are achieved.

10 Claims, 4 Drawing Figures

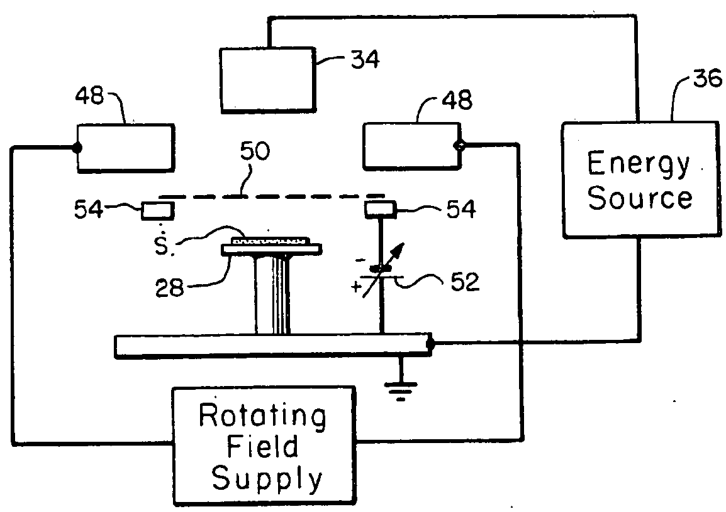

FIG. 2

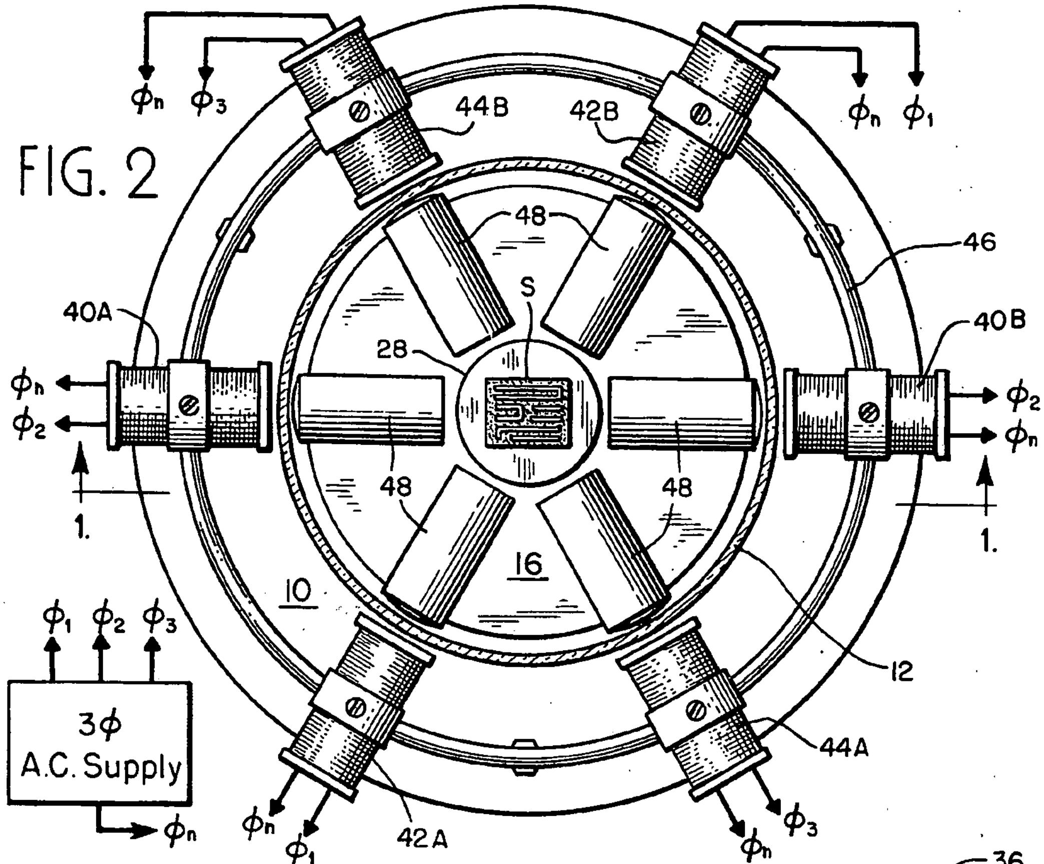

FIG. 1

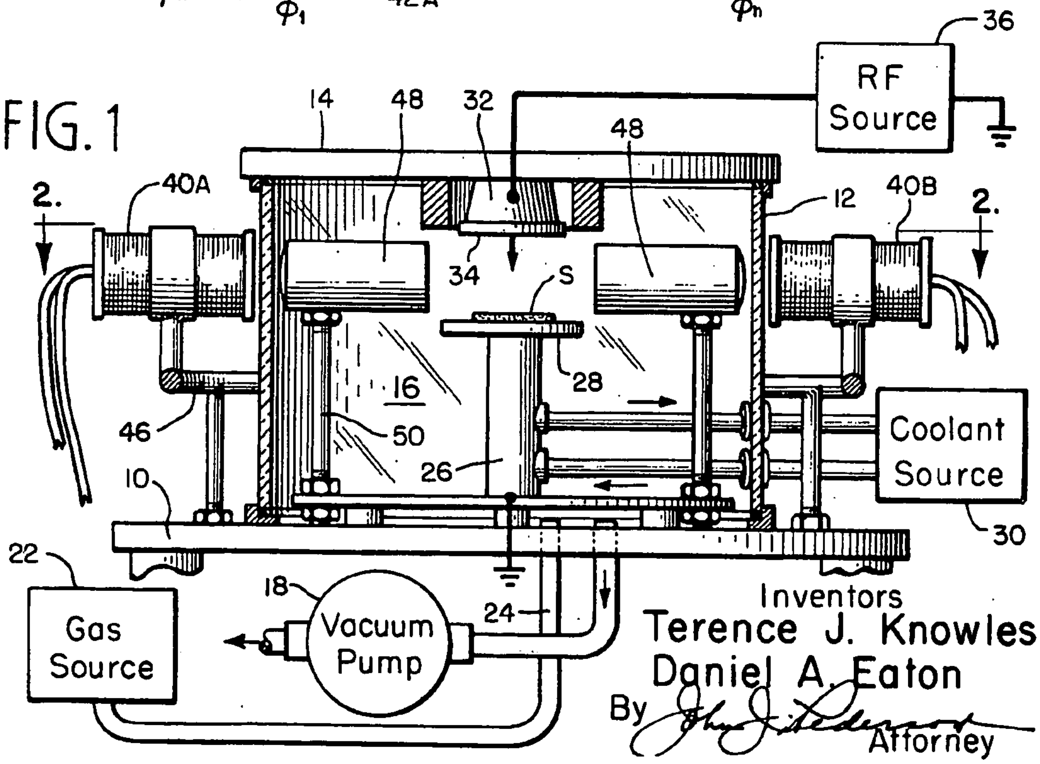

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FIG. 3

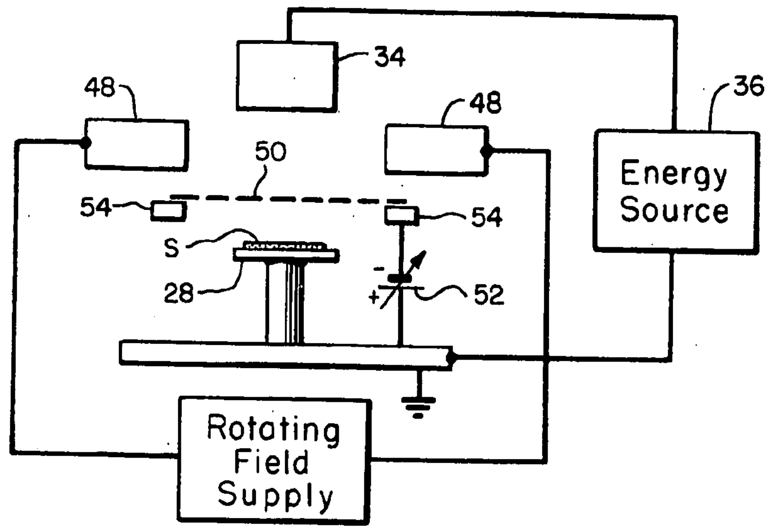
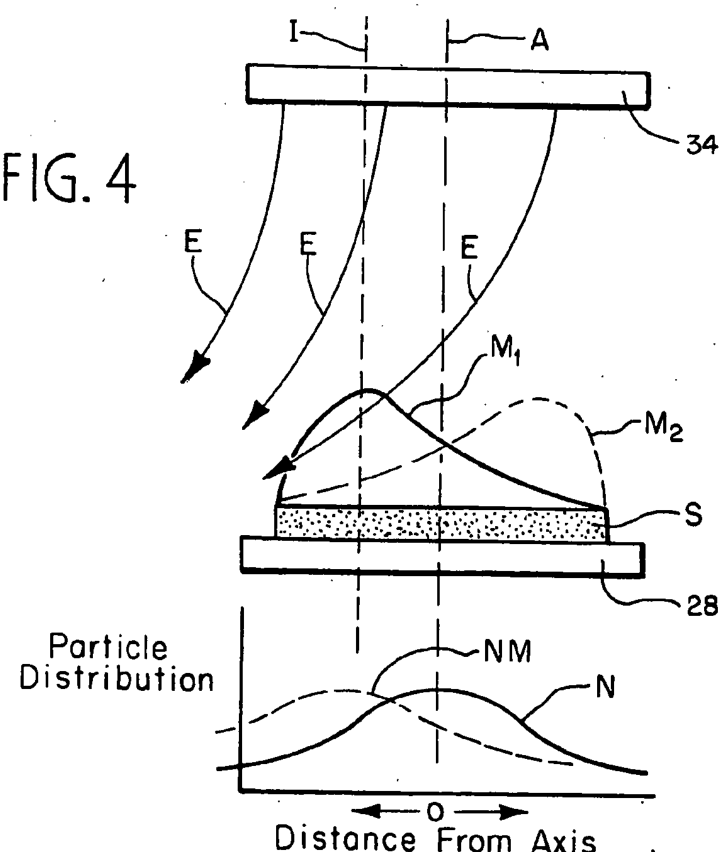


FIG. 4



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METHOD AND APPARATUS FOR APPLYING A FILM TO A SUBSTRATE SURFACE BY DIODE SPUTTERING

BACKGROUND OF THE INVENTION

This invention relates to film-forming techniques. More particularly, it pertains to improvements in the art of sputtering thin films of virtually any desired materials, such as insulators, conductors or cermets, for example.

The application of thin films to substrate surfaces by sputtering is a well-known and conventional technique. In practicing this technique, a cathode composed of or coated with a layer of the material from which the film is to be formed is mounted in a closed chamber filled with a gas mixture at a pressure corresponding to a reasonably high vacuum. The substrate is supported with the surface to be coated spaced from the cathode surface. An electric field is established by connecting the cathode and an anode across a suitable electric potential source. Upon the establishment of the electric field, the gas becomes ionized and the ions bombard the cathode surface with energy sufficient to dislodge cathode material which spreads throughout the chamber. A certain portion of the particles is deposited on the substrate surface.

In addition to dislodging molecular or atomic particles, the ions bombarding the cathode surface also cause the emission of electrons which are accelerated by the electric field to relatively high velocities and, upon striking the substrate, develop a considerable amount of heat. Because of such heat generation, most sputtering apparatus includes a circulating water system or the like for cooling the substrate support with which the substrate is in contact. Despite such substrate cooling and even at modest deposition rates, the dissipation of energy in the substrate often is sufficient that it melts, shatters or distorts.

It is a primary object of the present invention to provide methods and apparatus for depositing film on substrate surfaces in which the aforementioned heating effect is minimized or at least reduced to an acceptable level.

In the past, the above-described heating effect in sputtering operations has been reduced, where the substrate is parallel to the cathode surface, by applying a static magnetic field perpendicular to the electric field. The magnetic field deflects electrons from their normal path from cathode to substrate and, by suitably adjusting the strength of the magnetic field, all or a large portion of the electrons can be deflected to paths such that they do not strike the substrate surface and hence do not generate heat in the substrate.

While the application of a magnetic field in the foregoing manner is satisfactory in many instances, it does not lend itself well to applications where a uniform or otherwise controlled film thickness is essential, as, for example, in coating miniature electrical circuit components. When a magnetic field is applied to deflect the electrons to one side of their normal path, it has been found that this results in an increased density of electrons at one side of the cathode-substrate axis and the increased number of electrons in this region gives rise to a corresponding increase in the ionization of gas in this region. Thus, upon the application of a magnetic field to deflect the electrons, a situation is created wherein the cathode surface is subjected to a heavier bombardment of ions at one side than at the other. This, in turn, results in a heavier or more dense deposition of the molecular or atomic particles toward one edge of the substrate and a corresponding lighter or less dense deposition near its opposite edge. For electrical circuit components wherein a uniform film thickness is required, the nonuniform deposition resulting from the application of a stationary magnetic field is unacceptable.

It is, accordingly, another object of the invention to provide methods and apparatus for depositing, by sputtering, a film of uniform thickness on a substrate without overheating the substrate.

It is another object of the present invention to provide methods and apparatus that enable film deposition at increased rates.

A further object of the present invention is to provide methods and apparatus for depositing films of accurately-controllable thickness distribution.

Still another object of the present invention is to provide methods and apparatus for depositing a composite film made up of two dissimilar materials.

A still further and more detailed object of the invention is to provide a sputtering apparatus operable to deposit a film on a thermally fragile substrate.

SUMMARY OF THE INVENTION

The practice of the present invention involves use of a sputtering technique wherein the surface of a cathode is located in space-opposed relationship to the substrate surface. The operation takes place in a gas environment. An electric field, having a polarity and strength operable to ionize the gas and to bombard the cathode surface with gas ions, causes the cathode to emit electrons as well as to dislodge minute particles of material from the cathode surface. A magnetic field extends transversely through the space between the cathode and substrate to deflect electrons emitted from the cathode transversely clear of the substrate. The magnetic field is moved in a selected manner in order to achieve a desired distribution of particles within the deposited film. To achieve uniform film deposition, the magnetic field is rotated about an axis or path extending between the cathode and the substrate being coated.

The features of the present invention which are believed to be novel are set forth with particularity in the appended claims. The invention, together with further objects and advantages thereof, may best be understood by reference to the following description taken in connection with the accompanying drawings, in the several figures of which like reference numerals identify like elements, and in which:

FIG. 1 is a simplified vertical cross-sectional view through a sputtering apparatus embodying the present invention;

FIG. 2 is a cross-sectional view taken approximately on line 2—2 of FIG. 1;

FIG. 3 is a schematic diagrammatic view of a second embodiment of the invention; and

FIG. 4 is a diagrammatic view illustrating certain aspects of the operation of the FIG. 1 embodiment.

Referring first to FIGS. 1 and 2, a sputtering apparatus includes a metal base plate **10** upon which is mounted and sealed a hollow cylindrical glass wall **12** having a cover **14** mounted and sealed upon its upper end. Base plate **10**, wall **12** and cover **14** cooperatively define a sealed chamber designated generally by the numeral **16** and which can be evacuated by a vacuum pump **18** whose inlet conduit **20** is led into chamber **16** through base plate **10**. In the usual case, better results are achieved if the residual gas atmosphere within the chamber is a gas other than air. Hence, a gas source **22** is also connected to chamber **16** via a conduit **24**. Typically, the gas supplied from source **22** is argon or an argon-oxygen mixture, and a pressure of about one micron of mercury is maintained in chamber **16**.

Within chamber **16**, a substrate support pedestal **26** is fixedly mounted upon base **10** and has at its upper end a support platform **28** upon which a substrate S, which is to be coated, is supported. Pedestal **26** and platform **28** are of electrically conductive material and are electrically grounded. Preferably, pedestal **26** and platform **28** are actively cooled during operation of the apparatus, as by a circulating coolant system designated generally by the numeral **30**. A cathode assembly **32** of conductive material depends from cover **14** and includes a cathode element **34** which is either formed from the material which is to constitute the film applied to the substrate or is provided with a layer of the desired material on the cathode surface which faces the substrate support platform. The cathode is electrically connected to one side of a suitable electric power source the other side of which also is connected to ground. As indicated schematically, the power in this case is

supplied from a radio-frequency power source **36** which typically operates at **13.65** Megahertz.

The structure described thus far represents a conventional and well-known sputtering apparatus. In operation, the application of power between ground and cathode **34** establishes an electric field between the cathode surface and substrate support platform **28** which acts as an anode. The electric field ionizes the residual gas in chamber **16** and the gas ions are electrically attracted to and bombard the lower surface of cathode **34**.

The ion bombardment causes particles of the cathode material to be ejected from the cathode surface. On being dislodged, they spread out in directions which are more or less mechanically determined by the transfer of momentum from the bombarding ion that causes their dislodgement from cathode **34**.

While the direction in which the particles leave cathode **34** is dependent on many factors, the characteristics of the system as illustrated are such that the distribution of particles from cathode **34** is most dense at or close to the center of the substrate and falls off as the radial distance outwardly from the center increases. This decrease in density occurs approximately as a cosine function. The metal particles thus coat the exposed surface of the substrate S heaviest near its center, while the thickness tapers off at greater radial distances from the center.

Also leaving cathode **34** are electrons which are accelerated by the electric field and are confined by that field to paths perpendicular to the cathode and support platform surfaces. The strength of the electric field is sufficient that the electrons emitted from cathode **34** are accelerated to high velocities and thus impart a substantial amount of energy to the surfaces which they strike. This action induces considerable heating in substrate S. Coolant system **30** seeks to dissipate such heat from pedestal **26**.

As here employed, the described apparatus is especially concerned with use of the sputtering technique described above for coating substrates which may be thought of as being "thermally fragile" due to their physical characteristics or size. The term "thermally fragile" is used to characterize a substrate which would be adversely affected by the electron heating effect just discussed.

In accordance with the invention, to eliminate or at least materially reduce the heating effect of the electron bombardment of substrate S, the metallic particles are sputtered through a moving magnetic field. The field extends transversely across the space between cathode **34** and substrate S at right angles to the electric field, and it is rotated about the central cathode-substrate axis.

As shown, the magnetic field is created by three opposed pairs of electromagnets **40A–40B**, **42A–42B**, and **44A–44B** respectively. As best seen in FIG. **2**, the magnets are symmetrically disposed about the central cathode-substrate axis and are supported upon a fixed frame **46** mounted upon base plate **10** to locate the respective magnets at the exterior of chamber wall **12**. The respective magnet pairs are electrically connected to a three-phase alternating current power supply so that each magnet pair is connected to one of the three phases. Like in an electric motor, this manner of connection creates a magnetic field that rotates around the central cathode-substrate axis.

In order to concentrate the magnetic fields generated by the electromagnet pairs located outside of chamber **16**, a series of magnetic pole pieces **48** are mounted within chamber **16** on a framework **50**, each pole piece **48** being axially aligned with a respective one of the external electromagnets. Pole pieces **48** are constructed simply as solid cylinders of a material such as soft iron that has a relatively high magnetic permeability. Preferably, the apparatus might well be constructed so that wall **12** more closely surrounds substrate S, rendering it unnecessary to employ the additional pole pieces **48**.

FIG. **4** illustrates the affect of the magnetic field upon the electron paths. The magnetic flux lines are assumed to be into the plane of the drawing. In the absence of any magnetic field, the normal path of the electrons emitted from cathode **34** would be perpendicular to the cathode surface. Upon the application of the magnetic field, however, the electrons are deflected to one side as indicated by paths E. Assuming for a moment that the magnetic field is stationary, the net result would be that the sputtered material is deposited upon substrate S more heavily on one side as represented by curve M_1. As shown, the thickness variation is grossly exaggerated for purposes of illustration.

The reason for such non-uniformity of distribution of the deposited particles may best be understood by reference to the graph in the lower portion of FIG. **4**. In this graph, the particle density distribution is plotted against radial distance from the central substrate-cathode axis A. Solid-line curve N illustrates the normal distribution of particles on substrate S which might be expected in the absence of a magnetic field. Curve N is symmetrical about a maximum peak on axis A and falls off to both sides with increasing distance from axis A. Again, the height curve N is grossly exaggerated for purposes of illustration. This curve represents a so-called normal condition which exists in the absence of a magnetic field and when the surface of cathode **34** is bombarded by ions uniformly over its entire area.

During operation, ionization is achieved by collisions between gas molecules and electrons emitted from cathode **34**. In the absence of a magnetic field, the ionization due to electrons emitted from cathode **34** is uniformly distributed about cathode-substrate axis A, except possibly at the cathode edge where the field is slightly higher. As a result, a symmetrical distribution of particles over the surface of substrate S would occur.

Again assuming the existence of a stationary magnetic field, the distribution of electrons in the space between cathode **34** and the substrate is altered by that field. The electrons effectively are biased toward one side of axis A as indicated by the paths E. In the presence of a stationary magnetic field, therefore, more electrons are located to one side of axis A as a result of which more ionization of the gas occurs in the region to that one side. Since more gas is ionized on that one side of axis A, more ions bombard that side of the cathode and, thus, more particles are deposited on that portion of substrate S.

The net effect of the application of the magnetic field, then, is to shift the particle distribution to one side, as represented by the position of curve NM in FIG. **4**. This is the reason for the similar shape of curve M_1. Another way of viewing this effect is to consider that the axis I of maximum particle distribution is shifted out of coincidence with the central cathode-substrate axis A.

The strength of the magnetic field is chosen to be such that substantially all of the electrons are deflected to paths which pass clear of the edges of substrate S. By deflecting the electrons in this manner, heating of substrate S due to electron bombardment is minimized or eliminated.

At the same time, the non-uniform distribution on substrate S is minimized or substantially eliminated by causing the magnetic field to rotate about axis A. Curve M_2 in FIG. **4** represents the particle distribution on substrate S when the magnetic field has been rotated 180° from the position at which it gave rise to the particle distribution indicated by curve M_1. In rotating the magnetic field, the non-uniform distribution is averaged out over 360° so that a substantially uniform distribution over the entire substrate surface is achieved. The particle distribution near the center of the substrate at axis A remains substantially constant while the particle distribution at greater distances from axis A is alternately increased and decreased relative to the average distribution.

In addition to achieving uniformity of particle distribution on substrate S, the spiralling of the electrons in the magnetic field substantially increases the length of the path of movement of the electrons through the space between cathode **34** and substrate S, and that correspondingly increases the possibilities of collisions between the electrons and gas molecules

or atoms to cause ionization. By achieving increased ionization, the corresponding increase in cathode bombardment effects a similar increase in the rate of deposition of particles upon substrate S.

Some of the particles dislodged from cathode **34** are deposited upon pole pieces **48** during operation of the apparatus. Such coating of pole pieces **48** with the cathode material is advantageous, since it in effect provides a seal coating and eliminates the possibility of contaminating substrate S with metal from the pole pieces. Moreover, location of the electromagnets themselves outside of chamber **16** avoids any possibility of contamination arising from the electromagnets.

While the optimum operating conditions of the apparatus shown in FIGS. **1** and **2** are normally determined by trial and error, the following example may be considered typical. Cathode **34** is of solid alumina (Al_2O_3) 4 inches in diameter and is spaced 6 centimeters from support plate **28** which is of copper. RF source **36** operates at 13.65 Megahertz and the magnetic field has a strength of 60 Gauss and rotates at 60 revolutions per second. Substrate S in this example is a borosilicate glass slide. With this arrangement, it has been found that the substrate temperature and deposition rate vary in approximately linear proportion to the power supplied from source **36**. For an RF power of 500 watts, the substrate temperature increase is about 80° Centigrade and the deposition rate is about 50 Angstroms per minute. Using the same physical set-up but without application of the magnetic field, the glass slides melted or shattered.

A modified embodiment is shown in the schematic diagram of FIG. **3**, wherein the film applied to substrate S is a cermet composed of insulating cathode material, such as alumina, and a metal, such as gold, from a grid-like screen **50**. With the exception of the presence of screen **50** and its support ring **54**, the apparatus of FIG. **3** is generally similar to that of FIG. **1**. Screen **50** is biased at a negative potential with respect to the grounded support plate **28** by a suitable adjustable DC source, shown schematically as a variable battery **52**.

Because it is biased negative with respect to the anode, screen **50** is likewise subjected to ion bombardment and molecular or atomic particles of the screen are dislodged and transferred to substrate S in the same manner as deposition of the particles from cathode **34**. In order to minimize, as much as possible, bombardment of screen **50** by electrons emitted from cathode 34, the screen preferably is supported below the magnetic field developed between pole pieces **48**. While the rotating magnetic field thus does not have any influence on electrons emitted from screen **50**, the potential difference between screen **50** and plate **28** is far less than that between plate **28** and cathode **34**. Consequently, any electrons that are emitted from screen **50** do not reach the high velocities attained by electrons emitted from cathode **34**. Thus, such screen-produced electrons have very little heating effect on substrate S.

The improvements contributed by the present invention have been seen to require but comparatively simple modification of what may be existing sputtering apparatus. By subjecting the sputtered cathode material to a rotating magnetic field, it is possible to achieve more uniform coating thickness throughout the substrate surface while at the same time reducing unwanted heating of the substrate. Moreover, the presence of the magnetic field enables an increase in the rate of deposition and localization of the plasma.

As described above with reference to FIG. **4**, the strength and speed of rotation of the magnetic field is selected so that what would be a non-uniformity in coating distribution is averaged out in each 360° of rotation so as to achieve the desired uniformity. Alternatively, the strength of the magnetic field may be changed so as purposefully to result in a controlled non-uniform or graded distribution of coating thickness. That is, by increasing the field strength so that the peaks of curves M_1 and M_2 are moved a greater distance from axis A, the result is to make the coating thicker toward the outside edges of the substrate. On the other hand, a decrease in the strength of the magnetic field permits the coating to be somewhat thicker toward the central region of the substrate. It can be seen, then, that analogous changes in the speed and constancy of rotation of the magnetic field can be utilized to affect the coating distribution. In any event, the magnetic field is moved relative to the cathode in some predetermined pattern selected in order to achieve a desired distribution of the coating particles within the coating film that is deposited.

While particular embodiments of the invention have been shown and described, it will be obvious to those skilled in the art that changes and modifications may be made without departing from the invention in its broader aspects, and, therefore, the aim is the appended claims is to cover all such changes and modifications as fall within the true spirit and scope of the invention.

We claim:

1. In a method of depositing a film on a substrate surface by a diode sputtering technique wherein a surface of a cathode is located with respect to the substrate surface in space-opposed parallel relationship in a gas environment, said cathode surface being aligned with said substrate surface on a cathode-substrate axis normal to said surfaces, and an electric field, having a polarity and strength operable to ionize the gas and to bombard the cathode surface with gas ions, is applied to cause the cathode to emit electrons and to eject material from the cathode surface, the improvement comprising the steps of:

deflecting said emitted electrons in a transverse direction clear of the substrate by establishing a magnetic field extending transversely through the space between the cathode and substrate;

and rotating said electron deflection direction by moving said magnetic field in a selected pattern relative to said cathode and substrate to compensate inequalities in ion density due to said electron deflection and mitigate substrate heating by said electrons while achieving a desired distribution of particles within said film.

2. In the method of claim **1** wherein said cathode surface and said substrate are positioned in parallel relationship to each other and symmetrically aligned with respect to an axis normal to said surfaces;

the improvement wherein said magnetic field is moved in rotation about said axis.

3. The method of claim **1** which further includes the steps of:

disposing a screen of a second material between said cathode surface and said substrate surface;

and maintaining a predetermined electric potential difference between said screen and substrate surface to effect disposition of said second material upon said film.

4. The method defined in claim **3** in which:

said magnetic field is confined to a region spaced from said substrate surface;

and said screen is disposed between said magnetic field and said substrate surface.

5. A diode sputtering apparatus for use in a system for depositing films of material upon a substrate, which system includes an envelope for containing an ionizable gas and means for introducing said gas within said envelope, said apparatus comprising:

an anode disposed within said envelope;

a cathode disposed within said envelope spaced from said anode and defining an axis therebetween, said cathode adapted to support said material to face said anode;

means for applying an electric field between said anode and cathode subjecting said gas to ionization and polarization and of a strength to effect bombardment of said cathode with ions of said gas having sufficient energy to dislodge from said surface layer particles that are attracted toward said anode;

means for disposing said substrate on said axis in the path of said particles;

and means for creating a magnetic field rotating about said axis with a strength sufficient to sweep electrons, travel-

ing along said path, outwardly from said axis away from said substrate.

6. In an apparatus for use in a diode sputtering system, which system includes means defining a closed chamber for containing a gas under low pressure and means for introducing said gas into said chamber, said apparatus including a cathode having a flat surface mounted in said chamber, a flat substrate support platform mounted in said chamber in spaced-opposed parallel relationship to said cathode surface and aligned therewith on a cathode-platform axis normal to said surfaces, and means for applying an electric field between said cathode and said platform, the improvement comprising:

means for deflecting said emitted electrons in a direction transverse to said axis to clear said substrate, including means for establishing a magnetic field extending transversely across the space between said cathode and said platform;

and means for rotating said electron deflection direction about said axis including means for moving said magnetic field relative to said cathode and said platform in a selected path about said cathode-platform axis.

7. Sputtering apparatus as defined in claim 6 in which said establishing means comprises a plurality of electromagnets mounted in diametrically opposed pairs externally of said chamber at uniformly spaced locations about said axis;

and said moving means comprises a multiphase alternating current power source connected to supply peak current to said electromagnets in succession to cause the peak magnetic field to rotate about said cathode-platform axis.

8. Sputtering apparatus as defined in claim 7 which further includes:

a plurality of magnetic pole pieces mounted in said chamber, each of said pole pieces individually being aligned respectively with one of said electromagnets.

9. Sputtering apparatus as defined in claim 6 which further includes:

means for supporting a grid-like screen, of a material dissimilar to said surface of said cathode, in said chamber at a location between said cathode and said support platform.

10. Sputtering apparatus as defined in claim 9 which further includes:

means for confining said magnetic field to a region spaced from said substrate, and in which said screen is supported within the space between said support platform and said magnetic field.

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